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Technical and economic evaluation of biogas capture and treatment for “Piedras Blancas” landfill in Cordoba, Argentina

Franco Matías Francisca^(a), Marcos Alexis Montoro^{(b)(*)}, Daniel Alejandro Glatstein^(c)

^(a) Ph.D. Adjunct Professor, Facultad de Ciencias Exactas, Físicas y Naturales Universidad Nacional de Córdoba and Independent Researcher, Instituto de Estudios Avanzados en Ingeniería y Tecnología (IDIT, UNC-CONICET), Córdoba, Argentina.

^(b) Ph.D. Adjunct Professor, Facultad de Ciencias Exactas, Físicas y Naturales Universidad Nacional de Córdoba and Assistant Researcher, Instituto de Estudios Avanzados en Ingeniería y Tecnología (IDIT, UNC-CONICET), Córdoba, Argentina.

^(c) Ph.D. Adjunct Professor, Facultad de Ciencias Exactas, Físicas y Naturales Universidad Nacional de Córdoba and Postdoctoral Researcher, Instituto de Estudios Avanzados en Ingeniería y Tecnología (IDIT, UNC-CONICET), Córdoba, Argentina.

(*) Corresponding author: Departamento de Construcciones Civiles, Facultad de Ciencias Exactas, Físicas y Naturales. Av. Vélez Sarsfield 1611 – Ciudad Universitaria – Córdoba – Argentina. Email: mmontoro@unc.edu.ar

Abstract

Landfill gas (LFG) management is one of the most important tasks for landfill operation and closure because of its impact in potential global warming. The aim of this work is to present a case history evaluating an LFG capture and treatment system for the present landfill facility in Cordoba, Argentina. The results may be relevant for many developing countries around the world where landfill gas is not being properly managed. The LFG generation is evaluated by modeling gas production applying the zero order model, Landfill Gas Generation Model (LandGEM - EPA), Scholl Canyon model and triangular model. Variability in waste properties, weather and landfill management conditions are analyzed in order to evaluate the feasibility of implementing different treatment systems. The results show the advantages of capturing and treating LFG in order to reduce the emissions of gases responsible for global warming and to determine the revenue rate needed for the project's financial requirements. This particular project reduces by half the emission of equivalent tons of CO₂ compared with the situation where there is no gas treatment. In addition, the study highlights the need for a change in the electricity prices if it is to be economically feasible to implement the project in the current Argentine electricity market.

Keywords: landfill; global warming; biogas; modeling; waste; variability

About the Authors

Franco M. Francisca, Marcos A. Montoro and Daniel A. Glatstein are professors at the Facultad de Ciencias Exactas, Físicas y Naturales - Universidad Nacional de Córdoba and researchers of the Instituto de Estudios Avanzados en Ingeniería y Tecnología (UNC – CONICET).

Implications

Methane has 23 times more greenhouse gas potential than carbon dioxide. Because of that is of great importance to adequately manage biogas emissions from landfills. In addition to that it is environmentally convenient to use this product as an alternative energy source since it prevents methane emissions while prevents fossil fuel consumption minimizing carbon dioxide emissions. Performed analysis indicated that biogas capturing and energy generation implies three times less equivalent carbon dioxide emissions, however a change in the Argentinean electrical market fees are required to guarantee the financial feasibility of the project.

Introduction

Landfill gas (LFG) production is a consequence of several physical, chemical and biological processes that take place inside sanitary landfills. LFG composition depends on many factors and variables, including solid waste composition and time inside the landfill, nutrient and water availability, pH and temperature (Aguilar Virgen et al., 2014a). Among these, biological reactions are the most important factor for LFG generation. Organic matter decomposition takes place in three primary stages: aerobic decomposition, acid phase non-methanogenic anaerobic decomposition and anaerobic methanogenic decomposition (McBean et al., 2007). Different authors indicate that the third stage can be divided into an anaerobic methanogenic unsteady stage, where CH_4 increases and N_2 and CO_2 decrease to their terminal value, and an anaerobic methanogenic steady stage, where the generation of CH_4 and CO_2 remains relatively constant (Farquhar and Rovers, 1973). In addition, a final maturation stage is sometimes considered, where CH_4 production drops as a result of the decreased biological activity due to nutrient limitation (Pohland and Harper, 1986; Pohland and Kim, 1999). Usually, in conventional

landfills, it takes from several months to several years to reach the anaerobic stage while for wet bioreactors this time can be significantly reduced (Pohland and Kim, 1999).

Many different compounds constitute LFG. The most important constituents are methane (CH_4), carbon dioxide (CO_2), nitrogen oxides (NO_x), oxygen (O_2), hydrogen sulfide (H_2S), ammonia (NH_3) and sulfur oxides (SO_x) (Tchobanoglous et al., 1993). Typically, LFG composition varies during the year and during the landfill life. However, its composition is commonly assumed to be 50% methane and 50% carbon dioxide for most practical purposes once the anaerobic methanogenic steady stage is reached (Sharma and Reddy, 2004; Themelis and Ulloa, 2007; US EPA, 2005).

Gas emission is one of the main concerns related to the operation and after-care of landfills. It is very important to consider an efficient LFG capture and treatment system because of environmental issues. Methane is explosive and can significantly increase the risk of explosion in the landfill and surrounding areas. In addition, its toxicity represents a risk for human, animal and plant life. Gas overpressure inside landfills represents important risks for liner and cover integrity and stability. Finally, methane migration in soils can cause vegetation stress in the surrounding area (Koerner, 2012).

Landfills are the third highest source of global anthropogenic methane emissions, responsible for approximately 9 to 12% of those emissions in 2005 (IPCC, 2007; GMI, 2011). There is currently an increasing concern for methane as a greenhouse gas, because its global warming potential is about 21 on a 100-year time horizon (Crutzen, 1991; IPCC, 2001). In contrast, the use of LFG as an energy source eliminates these problems and decreases fossil fuel usage. It was estimated that global warming went from an impact of 0.1 person equivalent (PE) for non-controlled dumps to

-0.05 PE for landfills with the best designs for leachate and LFG management facilities (Damgaard et al., 2011).

LFG capture and treatment efficiency depends on landfill cell geometry and design, cell covers, LFG capture system installation, operation, and treatment alternatives (Mønster et al., 2015).

Inside landfill cells, gas migrates upwards and diffuses through cover layers to finally reach the ground surface and emanate into the atmosphere. When properly designed, LFG capture wells have a capture efficiency of around 90 % (Yazdani et al., 2015). To guarantee this efficiency and to encourage LFG migration into the capture system, landfill liners and covers must be properly designed in order to hinder LFG diffusion into the atmosphere. LFG retardation efficiencies depend on cover conditions; for operating cells with an active LFG collection system, efficiency is around 35%, but when a temporary cover is placed, collection efficiency increases to around 65%. When final covers are placed, LFG collection efficiency depends on cover design; for compacted clay covers, efficiency is around 85%, but when a complementary geomembrane is used efficiency increases to 90 % (Amini et al., 2011; Staub et al., 2011; Spokas et al., 2006). The USEPA recommends a general capture efficiency of 75% for LFG project evaluations (USEPA, 1997).

After capturing LFG, a common treatment system is the direct burning in open or closed flares. Closed flares are most commonly chosen because of safety, efficiency and environmental impacts issues. Contaminant destruction efficiencies in closed flares are as high as 99%. When LFG is burned in electric power generators, contaminant destruction efficiencies are also as high as 99% while energy transformation efficiency is around 45% (Aguilar-Virgen et al., 2014; Niskanen et al., 2013; SEPA, 2004; personal communication with suppliers).

Equipment operation and performance may be drastically affected by the presence of impurities in the gas such as H_2S , siloxanes, etc, and therefore the inclusion of an appropriate filter for removing such impurities is of key importance (SEPA, 2004)

The objectives of this research are to determine the possibility of LFG generation in the Córdoba city landfill under current conditions, to determine the expected amount of LFG to be captured, and to evaluate different treatment systems to minimize the emission of LFG into the atmosphere. The purpose is to quantify the reduction in equivalent CO_2 emissions and the corresponding contribution to diminishing Global Warming Potential from the use of LFG recovery and treatment systems.

Site description

“Piedras Blancas” landfill is located in Córdoba (Argentina), 11 km south of Córdoba city downtown, at $31^{\circ}30'$ South and $64^{\circ}13'$ West. It is located close to National Highway 36, which connects Córdoba city with Río Cuarto city. The landfill is located 2.2 km from the closest neighborhood. The penitentiary of Córdoba is 3.2 km to the South, and 5.3 km to the south there is a small town named Bouwer.

This facility is located in an area characterized by an annual mean precipitation of 800 mm, with a mean temperature of 25.2°C in the summer and 12.1°C in the winter (Telesca et al., 2012; De la Casa and Nasello, 2010). The landfill cell has a projected area of 25 hectares with a mean depth of 26 meters. The total surface area of the facility is 60 hectares. Figure 1 shows the geographical location of the study site.

Figure 1 here

Córdoba and 18 other cities and small towns of the Córdoba metropolitan area have disposed their municipal solid waste in this location for the last 5 years. The first waste disposal at the site occurred on April 1, 2010 and it has a projected closure date in August 2016. The disposal rate of MSW is around 60,000 Mg month⁻¹. The landfill operator performs a manual waste classification program that includes a random truck selection and visual inspection every working day. The typical waste composition, as informed by the operator is as follows: 58.2% organic and food waste, 10.06% mixed paper, 12.51% plastic, 0.64% wood, 2.02% metals, 4.63% glass and 11.94% other. As in many developing countries, the most important class is food and organic waste (Aguilar Virgen et al., 2014b; Cho et al., 2012). Waste is compacted in 30 cm thick layers in the landfill. At the end of each operation day or after every five disposal layers, the waste is covered with 20 cm of compacted soil. According to site operators, the compacted waste dry unit weight reaches $10.92 \text{ kN m}^{-3} \pm 0.93 \text{ kN m}^{-3}$. The waste unit weight was determined in situ by means of the rubber balloon method in a similar way as for compacted soils (ASTM D2167; ASTM, 2015). Despite obtained unit weight seeming higher than expected values, Laner et al. (2011), Staub et al. (2011) and Kumar and Sharma (2014) reported similar results.

The original action plan of the site considered only a very simple gas management procedure, consisting in the construction of venting pipes finishing one meter above the landfill cover system. LFG has therefore been directly vented to the atmosphere with no treatment, disregarding the potential hazard for site operation and farmland neighbors. The LFG emissions through each venting pipe were regularly monitored every four months by a laboratory specialized in environmental chemistry. According to technical reports, the determination of

LFG emissions followed standard procedures, such as: a) Method 2/2000 for gas velocity and flow rate, b) Method 3A/2006 for oxygen and carbon dioxide concentrations, c) Method 4/2000 for moisture content, d) Method 11 for hydrogen sulfide, e) Method 10/2006 for carbon monoxide, f) Method 7E/2006 for nitrogen oxides, g) Method 6A/2006 for sulfur oxides, and h) Method 03C/1996 for methane determinations (Code 40, Part 60, Appendix A, CFR, 2016). Table 1 presents the results from the monitoring performed between September 2010 and February 2013. Table 1 also includes the emissions limits recommended by TA – Luft (FMENCNS, 2002) as reference values.

Methane appeared in the LFG emissions nine months after the beginning of operations, and the concentrations measured presented significant time variability. However, there is a clear trend of increasing CH₄ concentration over time, reaching values higher than 200,000 mg Nm⁻³ after 24 months of operation. Sulfur dioxide presented a relatively constant concentration, close to 10,000 mg Nm⁻³, during the monitoring period. The trend for hydrogen sulfide concentrations was presented unclear, however, with the latest determinations, showing a significant increase, in contrast to nitrogen oxides, which clearly decreased after the first year of disposal. Finally, carbon monoxide concentrations showed significant variations during the monitoring period. From Table 1, it is clear that concentrations of the compounds emitted are higher than the regulated concentration levels, and therefore it is extremely important to capture and treat the gas produced in this site.

Table 1 here

There is no leachate recirculation system in the landfill. The leachate management program includes only limited extraction of the fluid from leachate chambers located in the periphery of the cells and recirculating it by injecting it again inside the cell through pipes, when the leachate height above the bottom liner is greater than 30 cm.

Materials and Methods

In order to assess the quantity of gas generation in the site and the feasibility of its capture and treatment, fieldwork was performed in order to determine the general characteristics of disposed waste. Disturbed waste samples were obtained for visual qualitative classification, and for laboratory tests. After analyzing the available information, computational simulations were carried out in order to determine the expected quantity of LFG to capture and treat. From the analysis of gas and site characteristics, a capture system was proposed and modeled, and two treatment systems were proposed. After that, the project was financially evaluated in order to advise the decision makers about the best way to deal with this project. Finally, the reduction in equivalent CO₂ emissions was computed in order to quantify the environmental benefit of appropriate gas management.

Fieldwork

Fieldwork consisted in drilling two boreholes in the landfill by means of a rotatory drilling machine using a helical auger. No drilling muds were employed to stabilize the hole in order to avoid altering the chemical properties and moisture content of the samples. Waste samples were

recovered each meter. The boreholes had different depths, depending on the local conditions of the selected boring place, one with a depth of 12.0 m and the second with a depth of 5.0 m.

Laboratory tests

For each sample, the following tests were performed: water content, material passing #200 sieve, organic matter content and pH determination. For most tests, the general laboratory procedures for soil samples were followed.

Moisture content was determined by weight loss when heated in an oven at 105 °C for 24 h (ASTM D 2216; ASTM, 2015). Fine particle content was determined by wet sieving of the recovered waste sample over the #200 sieve (ASTM D 1140; ASTM, 2015). Organic matter content was indirectly determined by weight loss when calcinated in a muffle at a 600 °C for 4 hours (Gallardo et al., 1987; Bettiol et al., 2002). Finally, pH was determined by stirring 25 g of solid waste in 100 cm³ of distilled water. This mix was stirred for one hour and pH was measured in the supernatant fluid for two hours or until a constant value in time was obtained. More details on the laboratory tests performed can be found in Maciel and Jucá (2011) and Sivakumar et al. (2010).

Numerical simulations

LFG generation models use simple equations to represent the complex phenomena that take place during organic matter degradation inside landfills. These models aim to determine the amount of methane generated at different landfill ages. Four different models were implemented

in this research: the zero order model (USACE, 2013), triangular model (Tchobanoglous et al., 1993), Scholl Canyon model (Thompson et al., 2009) and LandGEM (USEPA, 2005).

There are also second order models available in the literature. The accuracy of first and second order models increases if they are calibrated from field measurements. Second order models require parameters of complex determination and, generally, uncertainties in parameter determinations have significant impacts on model results. The increase in precision of second order models compared to first order models does not justify the effort required to determine all the required parameters in the field or laboratory. Therefore, most models use first order formulations (Amini et al., 2012; Lamborn, 2012).

Table 2 shows the equations of the different models applied in this article. The zero order model does not consider the consumption of organic matter during the degradation process (Kamalan et al., 2011), the triangular model considers a linear increment of methane production during the first stage of the process and then linear decay for the second phase after reaching maximum production (Reinhart and Faour, 2005; Tchobanoglous et al., 1993). The Scholl Canyon and LandGEM models consider a first order decay for organic matter degradation. While most models tend to overestimate the quantity of gas generation, the LandGEM model tends to underestimate the quantities but, despite of this, it is one of the most used models worldwide for LFG quantity predictions (Amini et al., 2011; Kumar and Sharma, 2014; Ogor and Guerbois, 2005; Thompson et al., 2009).

Table 2 here

The most important parameters required in models are methane generation rate k and methane generation potential L_0 , both depending on solid waste composition, landfill management procedures and local weather. These parameters can be obtained from specific laboratory tests or by fitting field data (Amini et al., 2011).

Due to the limited data available, provided by the operator, in this work the values of these parameters were determined by following the procedure recommended by the Ministry of Environment of British Columbia, Canada (2009). Solid waste fractions were classified as relatively inert, moderately degradable and biodegradable. Then, weighted averages of L_0 and k were obtained, considering representative values of L_0 and k for each group. L_0 ranges from 20 $\text{m}^3 \text{Mg}^{-1}$ for relatively inert wastes to 160 $\text{m}^3 \text{Mg}^{-1}$ for biodegradable material, and k ranges from 0.02 year^{-1} for relatively inert material and 0.09 year^{-1} for biodegradable material.

For k determination, it was considered that there is no leachate circulation in the site and that the average precipitation level for Córdoba city is 800 mm year^{-1} . Under these conditions, methane generation rate was $k = 0.064 \text{ year}^{-1}$.

The solid waste in “Piedras Blancas” landfill was found to be composed of 30.12% relatively inert fraction, 10.5% moderately biodegradable fraction and 59.37% biodegradable fraction (Ministry of Environment, 2009). From this considerations, estimated methane generation potential resulted $L_0 = 113.6 \text{ m}^3 \text{Mg}^{-1}$.

The L_0 value is within the range of expected values according to Amini et al. (2013) and compares relatively well with the experimental L_0 value determined for a test site in Tucumán (Argentina), in which the L_0 was $167 \text{ m}^3 \text{ Mg}^{-1}$ (Mc Bean et al., 2007). For comparison purposes it has to be considered that the Tucuman test site is around 500 km north from Córdoba city and only classified waste is disposed. The value obtained also compares very well with L_0 values measured or recommended by other authors. Reinhart and Faour (2005) recommends to adopt a value of $100 \text{ m}^3 \text{ Mg}^{-1}$ when no data is available, Also Maciel and Jucá (2011) report a value of $123.9 \text{ m}^3 \text{ Mg}^{-1}$ for an experimental landfill in Recife, Brazil. Machado et al. (2009) also reports L_0 values around $140 \text{ m}^3 \text{ Mg}^{-1}$ determined by laboratory tests.

Installation design and financial analysis

To analyze the particular distribution of landfill cells in the site, vertical wells with a radius of influence of 30 m (USACE, 2013) were distributed over the plain surface of the cell in order to maximize the covered area of the cell. Then, horizontal pipe network geometry was analyzed for connecting vertical wells to the treatment facility. Finally, the blowers, flares and generators were selected based on mean expected gas flow.

Once installation alternatives were defined, the cost of wells and pipe installation was calculated, and the costs of equipments were determined. The costs of connection and transmissivity were obtained from the electric power utility of the province, the operational costs from suppliers' suggestions and the administration costs were estimated according to the landfill operator's suggestions.

A cash flow was performed for financial analysis. Network construction and equipment installation costs were considered as initial investment. Operational costs, administration costs, facility maintenance and safety costs, and power transmission costs were also considered for each period. The net present value of the project was determined for different situations: considering energy costs specified by the Argentine market for traditional energy, and considering energy costs for alternative energies. Finally, a back-calculation was performed in order to determine the required energy costs for a null net present value using the same internal revenue rate applied for different alternative energy projects in Argentina. All costs involved in the analysis were considered in United States dollars.

Green House Gas emission reduction

Green House Gas (GHG) emission reductions were calculated by considering GHG emissions in a scenario without the project and the corresponding emissions in the scenario with the project. Emission reductions are computed with eq 1 as recommended by CDM – ACM 0001 methodology (UNFCCC, 2015).

$$\sum_{y=0}^{y=project\ life} ER_y = \sum_{y=0}^{y=project\ life} BL_y - PE_y \quad (1)$$

where ER_y is the GHG emission reduction in a year y , BL_y is the GHG base line emissions in the scenario without the project and PE_y is the GHG emission in the scenario with the project.

Base line emissions are computed according to eq 2.

$$BL_y = (DM_{project,y} - DM_{BL,y}) \times EP_{CH_4} + EL_{LFG,y} \times CEF_{elect,y} \quad (2)$$

where $DM_{project,y}$ is the methane potentially destroyed by the project in the period y , $DM_{BL,y}$ is the methane destroyed in period y in the scenario with no project, EP_{CH_4} is the CO₂ equivalent GH effect potential of CH₄, $EL_{LFG,y}$ is the electricity that it is supposed to be generated by the LFG project in period y and $CEF_{elect,y}$ is the equivalent CO₂ emissions of the alternative source required to generate the same amount of electricity in the case of no project.

$DM_{BL,y}$ is considered to be zero in the no project situation, since if not captured and treated, CH₄ was supposed to be directly vented to the atmosphere. $DM_{project,y}$ is considered as the methane generated in the landfill and emitted to the atmosphere without treatment. The equivalent CO₂ concentration was determined, considering the Green House Gas potential of CH₄ as 21. $EL_{LFG,y}$ is the energy recovered by the project that, in the case of no project, has to be generated by another source, and finally $CEF_{elect,y}$ is the CO₂ emissions due to energy generation with the alternative source.

GHG emissions in the scenario with project (PE_y) are computed by considering the equivalent CO₂ emitted to the atmosphere by uncaptured CH₄ for the different LF cover efficiencies and adding the equivalent CO₂ emissions to the atmosphere after burning the methane either in the generators and/or in the flares. In both cases, methane destruction efficiency is considered.

Results obtained

Laboratory tests

Figure 2 shows the variation with depth of water content, fine particles, organic matter and pH. Note that an important change in moisture content occurs at a depth of 5.5 m. At that depth, moisture content increases from 15–20 % to well above 80%. Fine particle content presents an erratic trend with depth, and that trend might depend on the frequency and type of daily cover during landfill operation. Organic matter content presents a similar trend to that observed for moisture content, with a clear increase below the 4.0 m depth. Contrary to expectations, and with some oscillatory trend, pH tests revealed basic values around 8.5 in the whole depth. When considering these results, it is important to highlight that determinations were performed in a supernatant solution after a contact period.

From the classification data, the solid wastes are composed of around 58% organic matter, but laboratory tests reveal contents around 20%. However, it has to be considered that the boreholes were drilled in the first cells that were filled at the beginning of site operation 4 years prior to this study, and the samples recovered were in a state of very significant biological decomposition.

Landfill gas generation is maximized when moisture content is between 40 and 80%, based on wet weight of the waste, while biological activity is reduced for lower moisture content and essentially stops when moisture content is under 20% (ATSDR, 2001; Farquhar and Rovers, 1973). In addition, bacterial activity is efficient at a pH range between 5 and 9, since acidic conditions can contribute to metal removal from solids that can be toxic for methanogenic

bacteria (USACE, 2013). According to these characteristics, the conditions surveyed in “Piedras Blancas” site ensure suitable conditions for LFG production for the coming years.

Figure 2 here

Potential LFG generation

Figure 3 shows the potential LFG generation from 2010 to 2060 obtained from applying the models presented in Table 2, while Table 3 summarizes the main features of each curve obtained and the total gas generation obtained with each model.

Figure 3 here.

Table 3 here.

Figure 3a shows that the total amounts of gas obtained with the four models are very similar: 938,382,367 m³ for the zero order model, 942,505,920 m³ for the triangular model, 949,434,039 m³ for LandGEM and 969,282,858 m³ for the Scholl Canyon model. In addition, peak generation appears at about 5 years from the closure of the site. However, peak values were very different: 20,308,898m³ for zero order model, 144,560,160 m³ for the triangular model, 50,922,293 m³ for the LandGEM and 61,437,894 m³ for the Scholl Canyon model. Since the zero order model considers that LFG generation is directly proportional to the amount of waste disposed in the place, the predicted quantity remains constant after site closure. However, its

results are important in order to estimate the amount of gas and to verify the order of magnitude of LFG quantities obtained with other models. Further analyses in this article will consider only the results obtained by applying the LandGEM model, since this is one of the most accepted LFG generation models worldwide (Faour et al., 2007; Kumar and Sharma, 2014).

From the data reported by the operator, the solid waste (SW) composition presents temporal variability, which affects the conditions for gas generation. However, the average waste disposal rate at the site remains quite constant during the year, at close to 60,000 Mg month⁻¹. Given this, different scenarios were analyzed to determine the sensitivity of the model to the composition of the waste, in terms of its effect on L_0 . The variability in waste composition is considered as the changing contents of its different fractions as they were measured over the past 5 years (not shown). In addition, the impact of weather conditions on k and the amount of LFG were also studied, with precipitations ranging from 250 mm year⁻¹ to 2000 mm year⁻¹. From this analysis, the L_0 ranged from 100.5 m³ Mg⁻¹ to 126.8 m³ Mg⁻¹, while k values were between 0.031 year⁻¹ and 0.095 year⁻¹. Figure 3b shows the LFG generation results obtained for 33 different scenarios resulting from different combinations of k , L_0 and landfill management plans. The figure shows the expected range of possible values for the site and landfill, with dashed lines representing the upper and lower bounds of the expected range of LFG quantities. The results show a minimum LFG generation of 0.43 m³ s⁻¹ when $L_0 = 100.5$ m³ Mg⁻¹ and $k = 0.032$ year⁻¹, and a maximum LFG generation of 0.69 m³ s⁻¹ when $L_0 = 126.8$ m³ Mg⁻¹ and $k = 0.095$ year⁻¹. The average value of LFG generation is 0.58 m³ s⁻¹ when $L_0 = 126.8$ m³ Mg⁻¹ and $k = 0.038$ year⁻¹. Variations in L_0 and k change the shape of the LFG production curves. Increases in L_0 enhance the LFG peak values and induce a smooth decay in gas production over time. In addition, the

increase in k also reflects a great increase in LFG generation peak value but a steeper decay in gas production over time. The main difference in the consequence of L_0 and k change is that an increase of L_0 implies the generation of greater quantities of LFG, while the increase in k implies that the greatest quantities of LFG are generated in shorter times. A model sensitivity analysis performed from the results in Figure 3b shows that a change in k value of 55% (0.038 year^{-1}) from the reference value (0.069 year^{-1}) represents a 15% decrease in the peak value and total amount of generated LFG. Moreover, a 10% decrease in L_0 values also represents a 15% decrease in the peak and total amount of LFG generated.

Not all the potentially produced LFG can be profitable, as it depends on the efficiency of the capture system and of the landfill cover system. Cover systems play a key role in gas recovery, since their design and construction contributes to preventing LFG migration to the atmosphere through the landfill surface and limiting oxygen entry to the landfill (Spokas et al., 2006). As mentioned before, cover system efficiency for LFG capture mainly depends on the design selected.

Figure 4 shows the two alternative final cover systems considered for the closure of Piedras Blancas landfill. One of the systems is 80 cm thickness of low permeability (hydraulic conductivity $<10^{-8} \text{ m s}^{-1}$) compacted soil, while the other system is a 45 cm thickness of low permeability compacted soil and a 1.5 mm thick HDPE geomembrane. Both systems were proposed considering local regulations (Regulation 9612, Cordoba City Government, 1997) and USEPA (1993) recommendations. For the performance evaluation of the cover alternatives an 85% LFG collection efficiency was considered for the compacted clay cover and 90% LFG

collection efficiency for the compacted clay + geomembrane cover alternative. Also, an efficiency of 35% was considered for the active cell, and a 65% efficiency for cells with temporary covers. These efficiencies were considered for calculating CH₄ and CO₂ emissions.

Figure 4 here

In the case of the cover composed of compacted soil with a LFG capture recommended efficiency of 85%, the minimum, average and maximum of recoverable LFG determined are 0.37, 0.49 and 0.52 m³ s⁻¹, respectively. If a geomembrane is included in the cover system, the efficiency in LFG recovery increases to 90% and the minimum, average and maximum of recoverable LFG increase to 0.39, 0.52 and 0.62 m³ s⁻¹, respectively.

Gas capture and treatment proposal

The capture system designed consists of a network of interconnected horizontal pipes 1 m to 3 m below the final cover system connected with vertical pipes drilled in the waste. Wells are distributed considering an influence radius of 30 m in order to maximize gas recovery. Influence radiuses are extremely variable and depend on many factors including environmental factors, vacuum level, waste transmissivity, waste compaction and leachate height; however, for design purposes, an influence radius of 30 m is widely accepted and this is verified once constructed (Yazdani et al., 2015; USACE, 2013).

The vertical gas collection system consists of an excavation, 30 cm in diameter from the top of the cell and to a maximum depth set 2 m above the bottom liner. In the middle of this

excavation, a slotted PVC or HDPE pipe 110 mm in diameter, is placed and the space between the pipe and the waste is filled with a granular filter. The top of the hole is sealed by a transition sand layer and a bentonite seal, in order to prevent gas migration and the entry of surface air into the biogas capture pipe.

Horizontal pipes are disposed with a 1% slope directed to a low point, normally connected to a vertical pipe, in order to conduct all condensate formed in the pipes during gas flow. The resulting design requires 54 wells that cover 67% of the cell surface. Figure 5a shows the vertical well distribution in the cell, and the gas capture net. The capture net is divided into three subnets, each subnet with a main pipe that conducts captured gas to the treatment point. The capture system is complemented by three gas blowers with a maximum flow of $820 \text{ m}^3 \text{ h}^{-1}$ and an exit pressure of 425 HPa. Figure 5b shows a detail of the wells distribution in each subnet and the principal conducting pipes to the treatment plant.

Gas flow in the horizontal pipes was simulated by solving flow equations considering the Darcy – Weibach equation for head loss. The results confirmed that flow velocities in all pipes are below 12 m s^{-1} which is the maximum flow velocity recommended by USACE (2013).

Depending on the cover type, efficiency in LFG recovery and predominant conditions for LFG generation, gas flow ranges between $1300 \text{ m}^3 \text{ h}^{-1}$ and $2100 \text{ m}^3 \text{ h}^{-1}$.

Figure 5 here

Two different treatments for the recovered LFG were considered: a) direct gas burning, and b) gas burning with electricity generation. Both alternatives require a condensate removal system, biogas filters, flow and gas quality meters, and flares or power generators depending on the selected system. Appropriate filters are of key importance, since H_2S and trace elements such as siloxanes must be removed because they can affect equipment operation. H_2S can react with water to form sulfuric acid, and siloxanes can form silicon oxides, both of which can affect equipment integrity and service life.

Available torches in the market have an operating range between 20 to $1100 \text{ m}^3 \text{ h}^{-1}$. From the gas generation expected at this site, direct gas burning requires 4 torches with an operating capacity between 550 and $850 \text{ m}^3 \text{ h}^{-1}$. The installation of this equipment does not require the construction of any specific building other than a concrete slab of 160 m^2 for the flares.

For the alternative considering energy recovery, four power generators of 850 kWh need to be installed, equivalent to a plant of 3.4 MWh, which is in the range of system sizes with acceptable economic revenue (Bove and Lunghi, 2006). These generators have a capacity of $48 \text{ m}^3 \text{ kWh}^{-1}$ giving a LFG flow of $400 \text{ m}^3 \text{ h}^{-1}$ each. In addition, two torches need to be installed with a capacity of between 550 and $850 \text{ m}^3 \text{ h}^{-1}$ to be used if LFG overflow occurs. Power generators have to be installed in a closed building of 240 m^2 and the rest of the equipment outside on a 160 m^2 concrete slab.

For each alternative, materials and construction work were calculated and, with the equipment and personnel required, the cost of each alternative was estimated according the prices in the

local market. For the alternative of direct LFG burning, the estimated cost was US\$1,301,582 while, for the alternative including energy recovery, the estimated cost was US\$ 4,967,473.

Table 4 summarizes the items required for each alternative facility and the associated cost of each item. All costs are in US dollars.

Table 4 here

Analysis and discussion

A cash flow for the treatment alternative considering electricity generation was prepared. Two different situations were considered, one considering a price of US\$ 14.00 MWh⁻¹ as in the energy market of Argentina, and the second with a price of US\$ 127 MWh⁻¹ as paid for alternative energy projects in Argentina. According to the manufacturer, the operation cost of LFG power generators is US\$ 19 MWh⁻¹. Also, according to the manufacturer, the service life of the generators is 15 years, but for this analysis, a service life of 10 years was considered. No scrap value was considered for the generators at the end of the service life and their replacement was considered in order to reach a plant and landfill life span of 25 years. Facility maintenance and safety costs were considered as US\$ 44,000.00 month⁻¹. An additional cost of facility power consumption of US\$ 10,000.00 month⁻¹ was also considered. A cost of US\$ 23,000.00 month⁻¹ for electric transmission system maintenance was considered and a cost of US\$ 47,430.00 month⁻¹ for administrative issues. All investment required for the initial installation was considered at time zero of the project. The analysis results in a generation cost of US\$ 83 MWh⁻¹, which is clearly more expensive than the market price.

A net present value of –US\$ 16,950,339.24 was determined by considering a price of US\$ 14 MWh⁻¹, and –US\$ 4,354,776.77 by considering a price of US\$ 127MWh⁻¹. For both situations, a revenue rate of 20.77% was considered, as recommended for this type of project in Argentina. A back calculation performed using the same revenue rate of 20.77% requires a price of US\$ 166.07 MWh⁻¹ to have a zero net present value.

An analysis of greenhouse gas (GHG) emissions reveals that if biogas is not captured in the site, baseline CO₂ emissions (*BL*) in 25 years will be between 7,276,465 Mg and 3,635,865 Mg. To determine that, it was considered that an equivalent amount of electricity needs to be generated by other sources. For the energy calculation an electricity generator factor of 0.57 was considered for the LFG plant. In this case, 19,856 MWh year⁻¹ was considered to be generated by a natural gas plant with CO₂ emissions of 7x10⁻⁴ Mg kWh⁻¹.

However, if biogas is captured and burned, the equivalent CO₂ emissions savings would be between 3,523,229 Mg and 2,087,716 Mg considering a landfill cover system with 85% percent efficiency and a CH₄ destruction efficiency with torches and generators of 99%. In addition, if landfill cover efficiency rises to 90%, the equivalent CO₂ emission savings would be between 3,814,589 Mg and 2,246,890 Mg. It is clear that equivalent CO₂ emissions are considerably lower if biogas is properly captured and treated and, in addition, if capture efficiency increases only 5% (by the addition of a geomembrane), it represents a further decrease of 7% in equivalent CO₂ emissions. Obtained results confirm that biogas capture and treatment in small landfills in developing countries have significant technical, economic and environmental advantages.

Conclusions

The composition and main characteristics of disposed solid wastes were analyzed and a survey was also performed of current conditions inside the Piedras Blancas landfill in Córdoba city.

With the results, the amount of landfill gas that can be potentially generated at the site was estimated, and a capture and treatment system was proposed. A landfill gas management system was financially evaluated according to current Argentine market rules and the equivalent savings of CO₂ emissions were estimated. The main conclusions in this research can be summarized as follows:

- Physical and chemical conditions in the “Piedras Blancas” landfill cells permit LFG generation. The estimated quantity of LFG generation in the site ranges from 0.43 m³ s⁻¹ to 0.69 m³ s⁻¹.
- Two different cell cover systems were proposed, with LFG isolation efficiencies of 85% and 90%, respectively. For the treatment of this landfill gas, two alternatives were drawn up, one considering only LFG combustion and other considering energy recovery by electricity generation.
- Financial analysis revealed that the current price for electricity in the Argentine electricity market is not sufficient to warrant energy generation from LFG.
- The equivalent CO₂ emission analysis showed that the amount of CO₂ emitted into the atmosphere when the cells are covered including a LFG capture and treatment system, is two times lower than that expected when no capture and treatment systems are included. In addition, the use of a geomembrane in the cover system increases the system efficiency by 5% and enables the emission of 7% less equivalent CO₂ to the atmosphere.

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Table 1: Piedras Blancas' biogas composition and recommended maximum emission values TA-Luft (FMENCNS, 2002).

Compound	TA Luft recommended emission limits [mg Nm ⁻³ , dry gas at 3% O ₂ (24 h average)]	Piedras Blancas		
		Mínimum	Mean	Maximum
		value	value	value
		[mg N ⁻¹ m ⁻³]	[mg N ⁻¹ m ⁻³]	[mg N ⁻¹ m ⁻³]
		[%v v ⁻¹]	[%v v ⁻¹]	[%v v ⁻¹]
CO	80 (TA-Luft 2002)	18.75 (0.002%)	302.7 (0.024%)	625 (0.050%)
NO _x	200 (TA-Luft 2002)	0.002 (0.0000%)	1.24 (0.0001%)	4.84 (0.0002%)
SO ₂	35 (TA-Luft 2002)	0.03 (0.0000%)	6,811 (0.238%)	9,399 (0.329%)
CH ₄	10 (TA-Luft 1996)	0.00 (0.0%)	106,20 (14,868%)	225,650 (31,591%)
H ₂ S	5 (TA-Luft 1986)	0.0001 (0.000%)	4.52 (0.0003%)	14.71 (0.001%)

Table 2: Gas generation models

Model	Equation	Reference
Zero order	$Q = \frac{ML_0}{(t_0 - t_f)}$	(1) USACE (2013)
Triangular	$L_0 = \frac{1}{2} t_f Q_{sp}$	(2) Tchobanoglous et al. (1993)
Scholl Canyon	$Q_{CH_4} = \sum_{i=1}^n k L_0 M_i e^{-kt_i}$	(3) Thompson et al. (2009)
LandGEM	$Q_{CH_4} = \sum_{i=1}^n \sum_{j=0,1}^1 k L_0 \left(\frac{M_i}{10} \right) e^{-kt_{ij}}$	(4) US EPA (2005)

M = disposed waste mass [Mg]; L_0 = methane generation potential [$\text{m}^3 \text{Mg}^{-1}$]; t_0 = time before methane emission started [years]; t_f = time at the end of gas generation [years]; Q_{sp} = gas peak flow [$\text{m}^3 \text{year}^{-1}$]; t_d = time for complete waste degradation [years]; Q_{CH_4} = annual methane generation [$\text{m}^3 \text{year}^{-1}$]; i = time period increment; n = year of methane determination; k = methane generation rate [year^{-1}]; M_i = disposed waste mass at year i [Mg]; t_i = waste mass age accepted at year i ; $j = 0.1$ year increment; t_{ij} = Age of the j section of waste mass accepted at year i .

Table 3: Gas generation models results

Model	Zero Order	Lineal	Sholl Canyon	LandGEM
Gas Generated in the first year [Nm ³]	2,503,837	20,699,712	9,740,304	7,657,275.55
Gas generated at the peak period [Nm ³]	20,308,897.95	144,560,160	61,437,893.63	50,922,292.94
Time span for peak [years]	6	5	5	6
Gas generated in the last year [Nm ³]	20,308,897.96	40,320	2,453,053.88	3,463,573.30
Total gas generated in the period considered [Nm ³]	938,382,367.35	942,505,920	969,282,858	949,434,039.34

Table 4: Costs of installation components according to local suppliers.

Electricity generation alternative		
Item	Quantity	Price [US\$]
1 In site landfill instalation (wells, trenches, piping, etc.)	Global	570,797.72
2 Gas condensate chambers	3	13,599.13
3 Blowers	5	16,847.91
4 H ₂ S Filters	1	369,840.00
5 Control panel and instruments	4	134,000.00
6 Generators	4	3,369,581.05
7 Gas Flares	2	151,561.29
8 Building	Global	338,324.12
Total		4,964,551.22
Gas burning in flares		
1 In site landfill installation (wells, trenches, piping, etc.)	Global	570,797.72
2 Gas condensate chambers	3	13,599.13
3 Blowers	5	16,847.91
4 H ₂ S Filters	1	369,840.00
7 Gas Flares	4	303,122.58
6 Building	Global	33,335.79
Total		1,307,543.13

Figure captions

Figure 1: Geographical location of the study site.

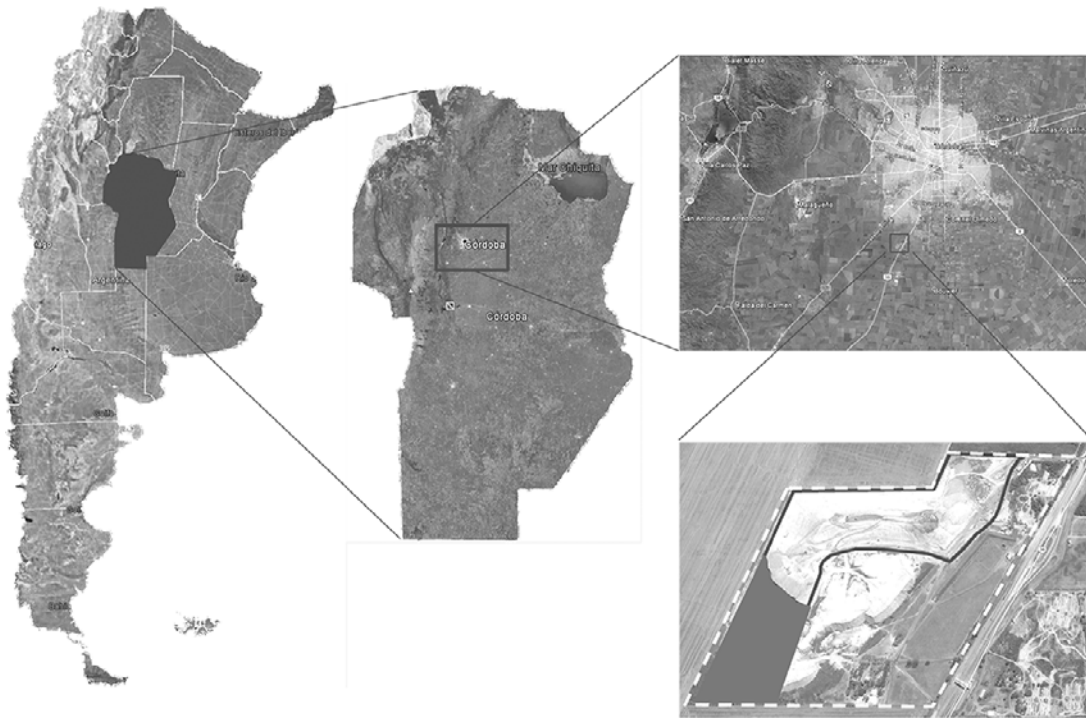


Figure 2: Disposed waste (a) moisture content; (b) fine particle content; (c) organic matter content; (d) pH.

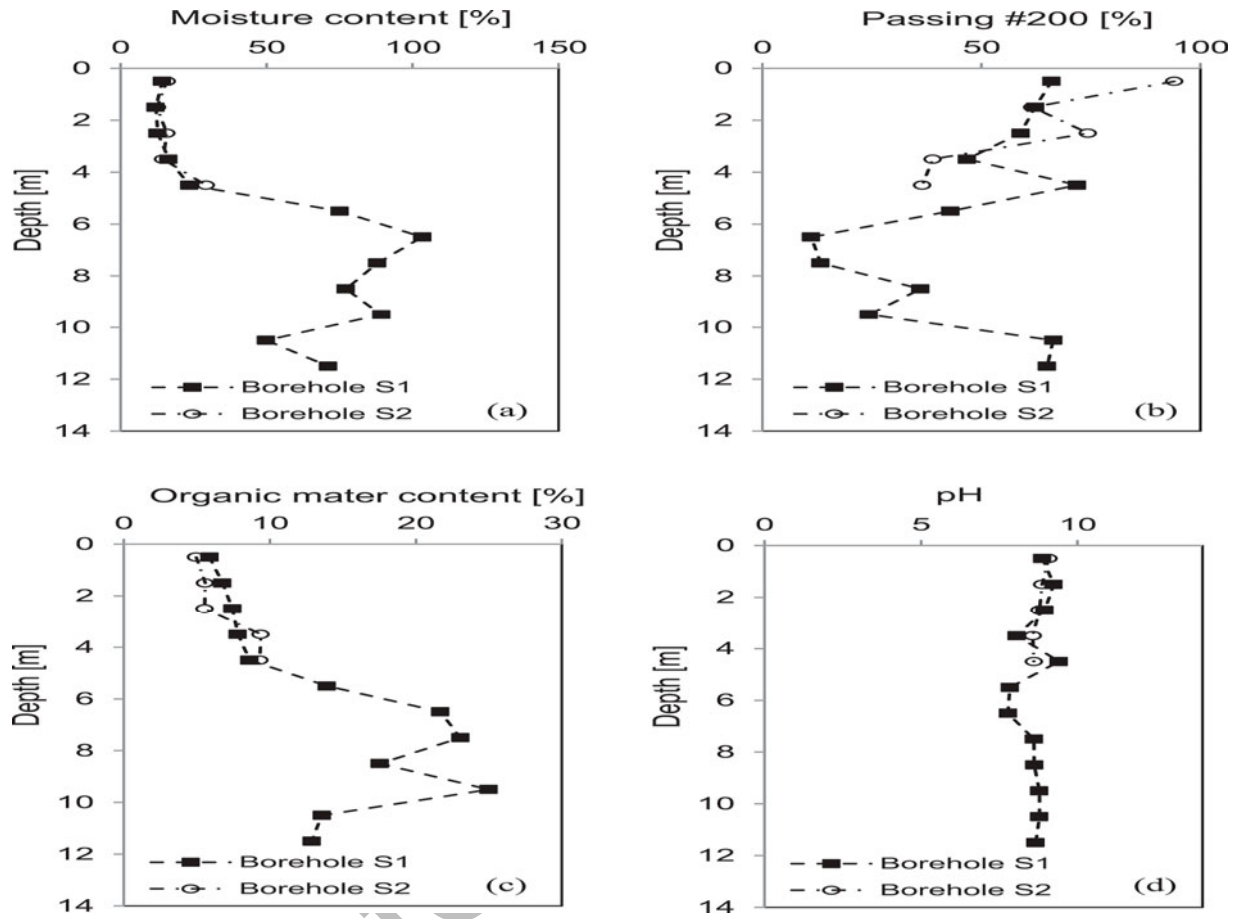


Figure 3: LFG generation: (a) zero order model, triangular model, Scholl Canyon model and LandGEM; (b) Sensitivity of expected gas generation considering the variability in L_0 and k due to variability in waste composition, expected mean annual precipitation, and landfill management plans. Dashed lines represent upper and lower bounds of expected values for the different scenarios.

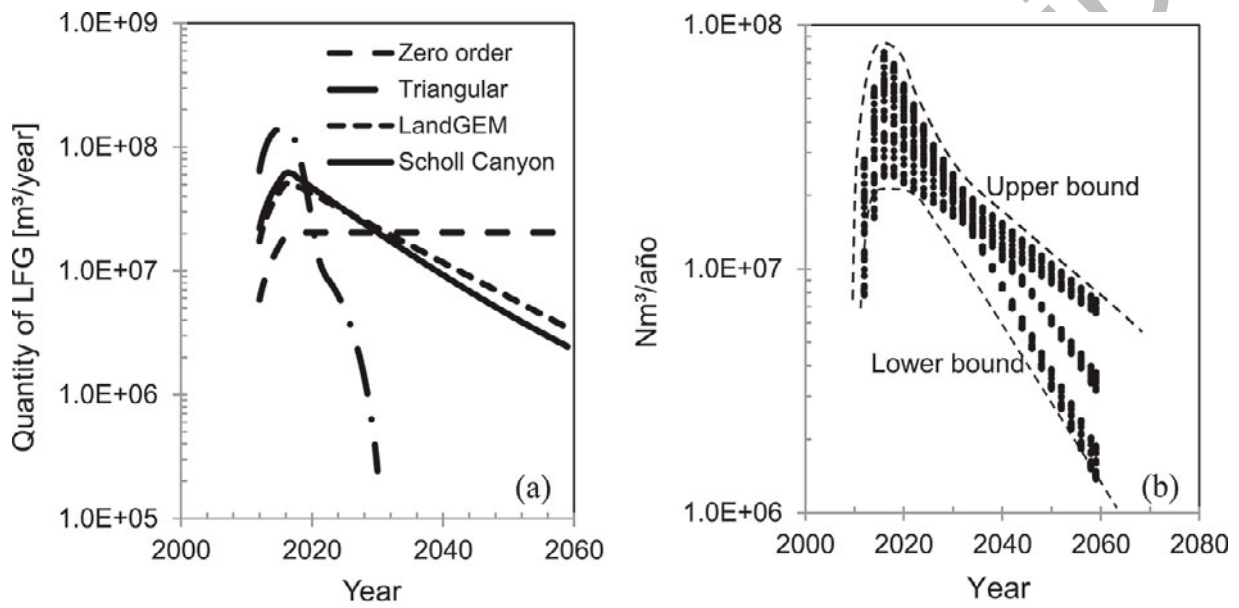


Figure 4: Proposed cover system for “Piedras Blancas” site closure.

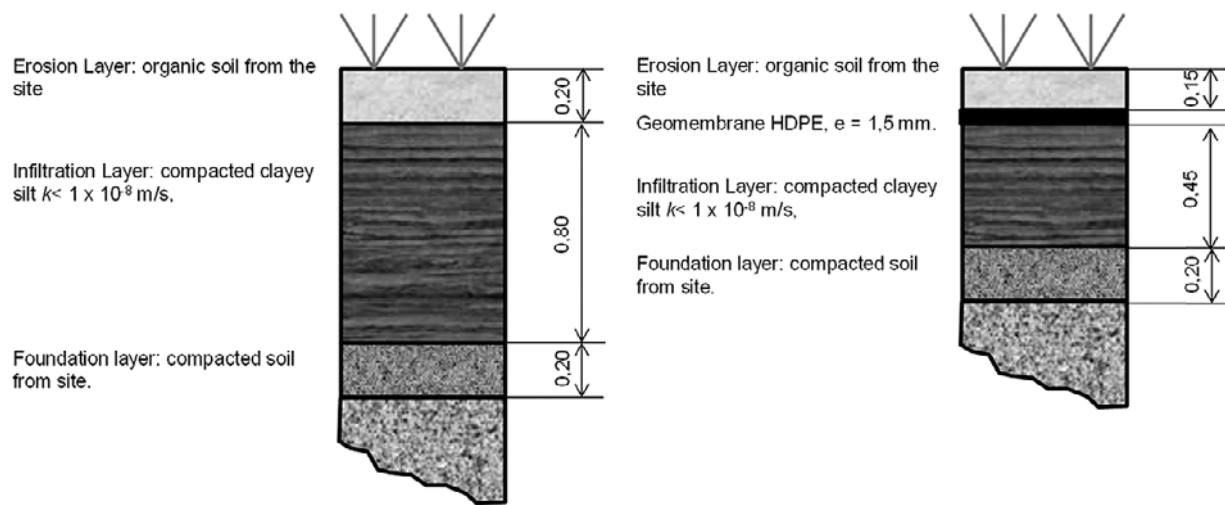


Figure 5: (a) Biogas capture network, (b) Detail of subnetworks.

